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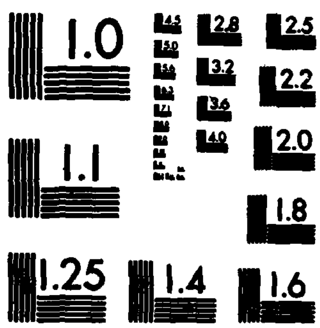

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A novel installation was developed for unshielded measurements of the neuromagnetic field near the scalp with a cryogenic system incorporating nine SQUID sensors in a single dewar. Five dc-SQUIDs measure the field of interest sensed by a radial array of five detection coils, while four rf-SQUIDs monitor three components of the ambient field and the axial gradient. The latter are applied to electronic cancellation of background noise. The dewar is mounted in a scanning device for rapid and accurate positioning about the head. This system provides major advantages over conventional single-sensor systems.

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MAGNETOENCEPHALOGRAPHY WITH AN ARRAY OF SQUID SENSORS

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A novel installation was developed for unshielded measurements of the neuromagnetic field near the scalp with a cryogenic system incorporating nine SQUID sensors in a single dewar. Five dc-SQUIDs measure the field of interest sensed by a radial array of five detection coils, while four rf-SQUIDs monitor three components of the ambient field and the axial gradient. The latter are applied to electronic cancellation of background noise. The dewar is mounted in a scanning device for rapid and accurate positioning about the head. This system provides major advantages over conventional single-sensor systems by greatly reducing the time for mapping a field pattern, maintaining approximately 1 mm accuracy in positioning over the scalp, and permitting correlation analysis of activity occurring simultaneously at nearby locations.

INTRODUCTION

Superconducting magnetic sensors are being effectively used in fundamental studies of brain function underlying sensory and cognitive processes,[1-3] and in clinical research designed to test the ability of such sensors to locate small tumors and foci of epileptic seizures.[4,5] With the worldwide interest and participation in this type of research becoming far greater than it was just a few years ago, the outline of the shape of future research in neuromagnetism is already visible. Locating sources within the brain requires the use of small sensing elements of high sensitivity so that detailed maps of the field pattern may be constructed from measurements external to the scalp.[6] Such high resolution maps must be based on measurements at many positions. Ideally, these should all be made at the same time, for otherwise there is a danger of variation in the measures caused by time-dependent changes in the state of the subject's brain. The device described here for measurements in an unshielded environment represents an important step between the conventional single magnetic sensor and such a large array.

The system described here relies on a sensor that is also most likely to be incorporated in the multi-sensor of the future: the SQUID (superconducting quantum interference device).[7,8] To discriminate between the localized neuromagnetic field of interest and fields from more distant noise sources, the SQUID is conventionally used in conjunction with a closed superconducting input circuit consisting of a detection coil and an input coil, the latter being mounted close to the SQUID so that they are magnetically coupled. A superconducting shield surrounds the SQUID and input coil, to insure that the detection coil provides the

only contact with the magnetic environment. Thus, when a magnetic field links the detection coil, a current proportional to the net flux is set up in the superconducting input circuit so as to keep the total flux in the circuit unchanged, and the SQUID responds to the magnetic field imposed on it by the input coil. This response is monitored by appropriate electronic circuits, so that the output of the SQUID electronics is proportional to the net magnetic flux in the detection coil. The entire arrangement of detection coil, input coil, and SQUID is kept superconducting by immersion in liquid helium contained in a dewar. The detection coil is usually designed so that uniform fields and fields with uniform gradients (those that are associated with distant sources) have sharply attenuated effects. A first-order gradiometer (two axially separated opposing coils) is effective in remote locations, and a second-order gradiometer (two opposing gradiometers) has proved sufficient for many purposes in an urban environment.

The desireability of incorporating several SQUID sensors within a dewar was recognized by Cohen[9] whose two-SQUID system made simultaneous measurements of the change in strength of the field normal to a surface along two orthogonal transverse directions. Also investigators at the Helsinki University of Technology developed a system incorporating four SQUIDs and accompanying first-order gradiometers.[10] However, both of these systems were designed for use in magnetically shielded environment and cannot be used in a normal laboratory or hospital setting. We shall describe a system that was developed for use in such magnetically unshielded environments.

MAGNETIC SENSOR

A novel aspect of the present system is its use of electronic cancellation to improve the rejection of uniform fields and uniform field gradients by the gradiometers. The effectiveness of a gradiometer depends on how well "balanced" it is in terms of matching the area-turns product between its various coils. Mechanical winding provides a balance of only 1% or so, which is insufficient to derive maximum benefit. Conventionally, small superconducting loops or tabs are then placed at appropriate positions near the coils to improve the balance by disturbing applied fields in such a way as to compensate for small errors in coil fabrication; and three smaller adjustable loops or tabs are arranged with control rods extending through the top of the dewar. Once the system is cold, the rods permit fine improvement in balance, as indicated by the rejection of a uniform field when applied in each of three orthogonal directions. Such mechanical adjustment becomes impractical when considering multi-sensor systems, and for that reason a system was developed whereby additional sensors are included within the dewar to monitor the ambient field, as well as one field gradient, and permit electronic subtraction of these references from the signals of interest. The effectiveness of such "electronic balancing" in a laboratory environment was demonstrated by Bastuscheck with two single sensor systems with second-order gradiometers in the Neuromagnetism Laboratory at N.Y.U.[8] The present system contains five sensors for measuring the neuromagnetic signals of interest and four sensors for monitoring three orthogonal components of the ambient field and the field gradient along the dewar's axis. Detection coils for the former will be called "signal" coils and for the latter, "reference" coils.

(a) SQUID systems

The assembly of nine SQUIDs and detection coils is mounted on a probe that is suspended within a fiberglass dewar of 10 liter capacity, as shown in Fig. 1. The SQUIDs are mounted within a superconducting shield positioned at the bottom of the dewar's helium reservoir. Shielded superconducting leads connect the input coils of the SQUIDs to their respective detection coils, which are supported by a frame braced securely against the bottom of the dewar's tail. The frame is enclosed by a protective cover and a metal foil to shield the detection coils from rf interference which may degrade SQUID performance.

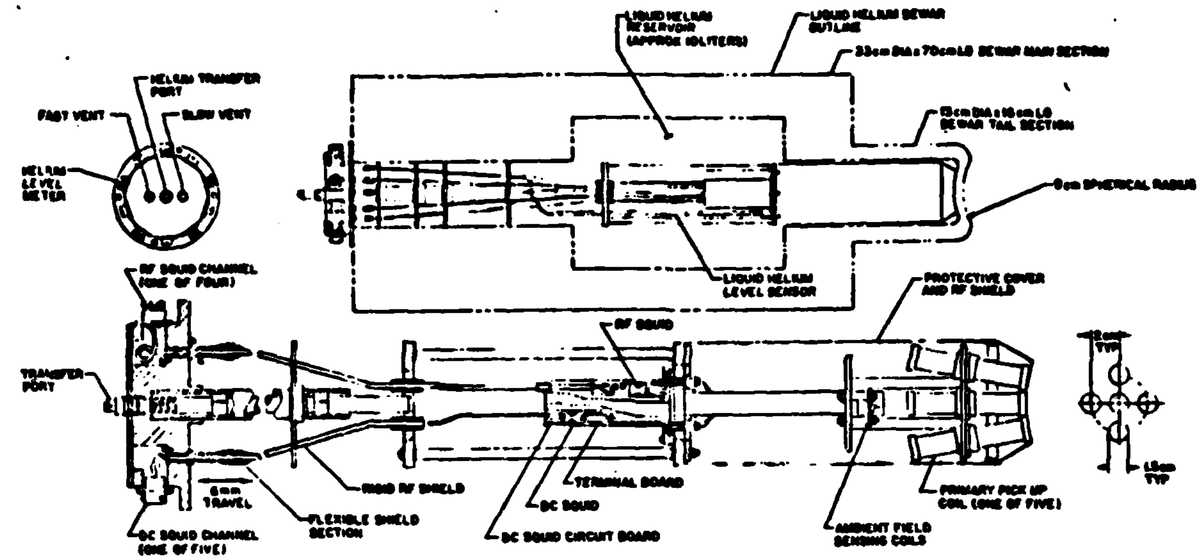

Fig. 1 Magnetic sensor: top view of the dewar, longitudinal section of the dewar, and longitudinal section of the probe

(b) Detection and Reference Coils

The array of five signal coils, each wound on a separate former, is positioned at the bottom of the dewar's tail; and about 3 cm above their tops are the four reference coils. The frame supporting this entire array can be dismounted easily from the probe, once the leads to the SQUID input coils are disconnected from their superconducting terminals.

The signal coils have the geometry of a second-order gradiometer with 1.5-cm diameter and 4.0-cm baseline between adjacent coils. Experience with a single sensor has shown that the neuromagnetic field normal to the scalp will display significant variations in strength over lateral distance of 1-2 cm for cortical sources. Therefore, the five signal coils were arranged in the pattern of a cross, with one central coil aligned along the dewar's axis and four equally spaced surrounding coils whose bottom coils lie on a 4.0-cm diameter circle. As shown in the x-ray view of Fig. 2, the axes of the four outer coils are tipped outward by 10 deg at the top so that they fall approximately on radii of a 9-cm sphere. With the center of the subject's head placed at the center of this spherical volume, the arrangement keeps all of the signal coils approximately radially oriented with respect to the head. The bottom of the dewar has a spherical concavity of similar radius to allow it to be positioned close to the scalp. The tilt of the outer coils places their axes on a 3.4-cm diameter circle at this outer face of the tail. Since each of these signal channels must have low intrinsic noise, the dc DYNABIAS™ SQUID was chosen as the sensor. Despite the proximity of the signal coils to each other, the cross-talk between channels is calculated to be less than 2%, and no measureable effect of this has been seen.

Fixed superconducting tabs or loops were permanently placed on the coil formers to provide a first-order improvement in the balance. Careful positioning provided a field balance on the order of 1 part in 10^4 and a gradient balance of about 1 part in 10^3.

The four reference coils mentioned above are wound on a common former shaped as a cylinder mounted just above the signal coils. The orthogonally oriented magnetometer coils sense the axial as well as the two transverse components of the ambient field, and a first-order gradiometer is oriented along the dewar's axis. Because of their configuration as magnetometers and first-order gradiometer, these

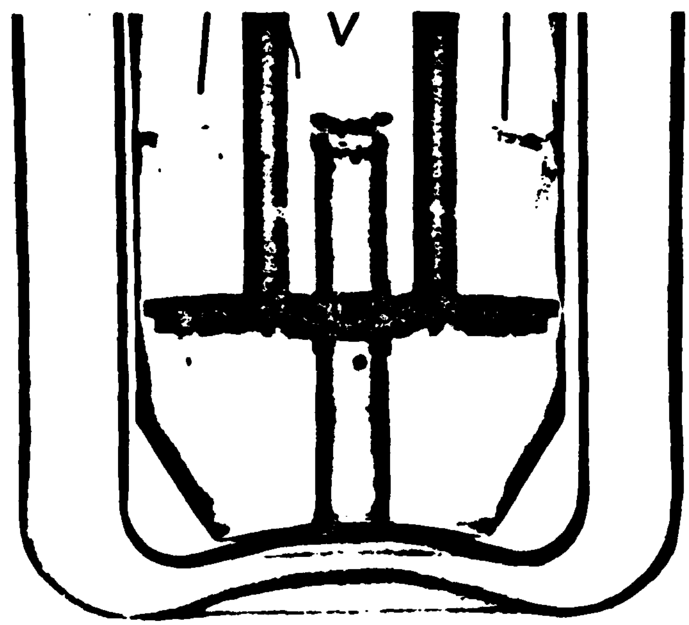

Fig. 2 X-ray of the dewar's tail showing the signal coil array

reference coils are strongly affected by the ambient noise. Therefore, it was possible to use a SQUID with lower sensitivity than those used in the signal channels, so the rf HYBRID™ SQUID was selected.

SCANNER

The dewar with its sensors is mounted in a specially designed holder, called Scanner, so that when moved the face of the tail sweeps over a spherical surface of selectable radius, while the dewar's axis remains pointing toward the center of the sphere. This arrangement constitutes a departure from the common procedure in neuromagnetism of orienting the dewar normal to the scalp at each location, a practice that had been adopted because heads are not truly spherical. However, keeping the axis of the dewar pointing to the center of the head is consistent with present models for the head, which assume it to be a sphere for the reason that this enables one to predict the field pattern from a given source location. Also, it is also more convenient to move the dewar about the head since only two (angular) variables must be controlled rather than three.

Scanner consists of a carriage which runs across a pair of arched, parallel rails of semicircular shape, whose ends are joined by a frame that is supported by axles so that the frame may rotate (Fig. 3). All of the components are fabricated from fiberglass, brass, and other non-magnetic materials of low electrical conductivity. The rails are machined from 13-mm thick G-10 fiberglass. The carriage is pulled in one direction or the other by a nylon parachute cord which runs over a set of pulleys, with a worm and worm gear arrangement which provides the mechanical advantage to drive a takeup drum for the cord. For safety, two independent sets of cords and drums are used, one on each rail. The position of the center of the carriage along the arch is designated by the polar angle in a spherical coordinate system. The carriage grasps each rail with two grooved wheels on top and one underneath. A rigid frame holds the rails at the ends, and the rails, together with the carriage and dewar, can be rotated as a set about their horizontal diameter. A worm and worm gear drive controls this rotation, which is easily done by virtue of counterweights suspended below the frame on rigid arms. This rotation angle is designated by the azimuthal angle in the spherical

Fig. 3 Scanner positioning the dewar above a subject

coordinate system. When the dewar is rotated by as much as 45° from the vertical, the flexing of the rails corresponds to less than 0.3° error in azimuth. Thus, the angular position of the dewar's axis can be established with a precision of better than 0.5 degree, corresponding to less than 1 mm at the scalp.

The height of the dewar in the carriage can be adjusted to accommodate heads of different radius. Also, the dewar may be rotated about its axis in the carriage, since it rests on nylon rollers precisely for this reason. When rotated, the center signal coil remains fixed in place, while the outer coils are rotated with the dewar for obtaining measurements at intermediate positions.

The frame holding the rails is supported by two panels of 5-cm thick particle board, which in turn rest on a wood frame and cork-rubber laminate pads for vibration isolation. We have not detected contributions to the noise spectrum of the signal channels or field reference channels from vibrations in the laboratory, which is on the 9th floor of a steel-framed building in Manhattan.

The subject sits on a chair or rests on an elevated bed, with his head supported by cushions to keep the center of the head coincident with the center of the arc traveled by the carriage. Verification of correct positioning is done visually by reference to pointers attached to Scanner. Visual, auditory, and somatosensory stimuli can be applied without difficulty in this open setting.

ELECTRONIC SYSTEM

The voltage outputs from each of the five signal channels and four reference channels are appropriately filtered before electronic balancing is performed on each of the signal channels. Figure 4 shows the block diagram of the electronic system. The voltages of the channels are applied to a separate bandpass filter which is set to a bandwidth of interest. The filters are matched to each other, have adjustable gain, and provide a rolloff of 48 db/octave. Subsequently, the outputs of each filter are applied to a comb filter designed to selectively attenuate noise at the power line frequency and its harmonics. Then the time derivative of each reference is taken in the interest of greater flexibility in compensating for the effects of eddy currents and hysteretic magnetic materials in the environment. These time derivatives and the original, filtered outputs of the reference channels are scaled by manual or computer-controlled attenuators and then subtracted from each of the five signals. Since different weights are assigned to the references and their time derivatives for each of the signals, a total of 40 "weights" must be selected. The signals with references removed are called the "summed signals." These summed signals are applied to anti-aliasing, low-pass filters before entering the analog-to-digital converter of a PDP 11/34 computer for subsequent analysis.

(a) Electronic Balancing

Thus far our experience indicates that adequate electronic balancing of the five signal channels can be accomplished manually in one hour or less. Field balancing is achieved by placing the entire system in an ac field (2 to 5 Hz) that is uniform and observing with an oscilloscope or lock-in amplifier the imbalance in each signal channel. The appropriate weights are then adjusted to minimize this imbalance. Then the field is applied successively in each of two orthogonal directions and the same procedure of adjustments is carried out with the other weights. Finally, a uniform gradient is applied in the axial direction, and the weights for the gradient reference are adjusted. It is prudent to iterate this process at least once to achieve an optimal balance.

To provide the uniform field used in balancing for two horizontal directions we constructed an array of two orthogonally oriented square Helmholtz coils, each about 2.7 m on a side. Each coil has 25 turns of 0.5 mm dia copper wire and can be driven by an ordinary function generator to produce a field of about 0.5 μT at its center. A similar Helmholtz set connected in series opposition provided a uniform field gradient in the vertical direction. To establish a vertical field with increased uniformity, a set of four coils[11] with turns ratios of 59:25:25:59 was made. The coils of this set and the vertical gradient set can be raised by ropes and pulleys when balancing is completed, to permit convenient access to Scanner and the subject.

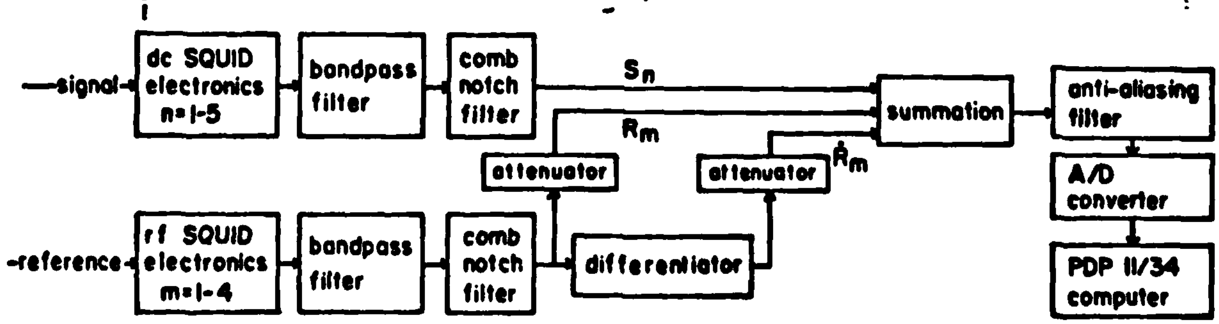

Fig. 4 Block diagram of the signal and reference processing electonics

Considerable care was invested in making the coils sets to insure maximum field uniformity. Despite the fact that spacing between coils was accomplished with an accuracy of better than 3 mm, studies of the field profiles showed that the steel reinforcement in the concrete floor of the laboratory has a noticeable effect, viz., the axial field and gradient centers were displaced by typically 1 cm from the geometrical center of the coils. Steps to remedy this by making one- or two-turn changes in the number of turns in appropriate coils had no effect on the noise spectra of the summed signals. This suggests that further precision in field and gradient balancing would have little or no practical consequencies in our particular laboratory environment.

INSTRUMENT PERFORMANCE

(a) Noise spectra

Measurements of the noise spectra of the signal channels without electronic balancing was carried out at S.H.E. Corporation in a light industrial area. Noise levels are expressed as the equivalent field noise applied to the lowest coil alone to produce the observed voltage noise at the output of the SQUID electronics. The spectral field density showed intrinsic system noise of about 20 $fT/Hz^{1/2}$ extending from high frequencies down to approximately 0.5 Hz. The ambient noise level in the Neuromagnetism Laboratory of New York University is several orders of magnitude higher at frequencies of ≈1 Hz than in the suburban environment, as indicated by the magnetometer references. An example of the laboratory noise level is shown in Fig. 5. At 10 Hz the amplitudes are comparable to published data for a hospital in Helsinki[12] and a laboratory in Berlin[13], whose

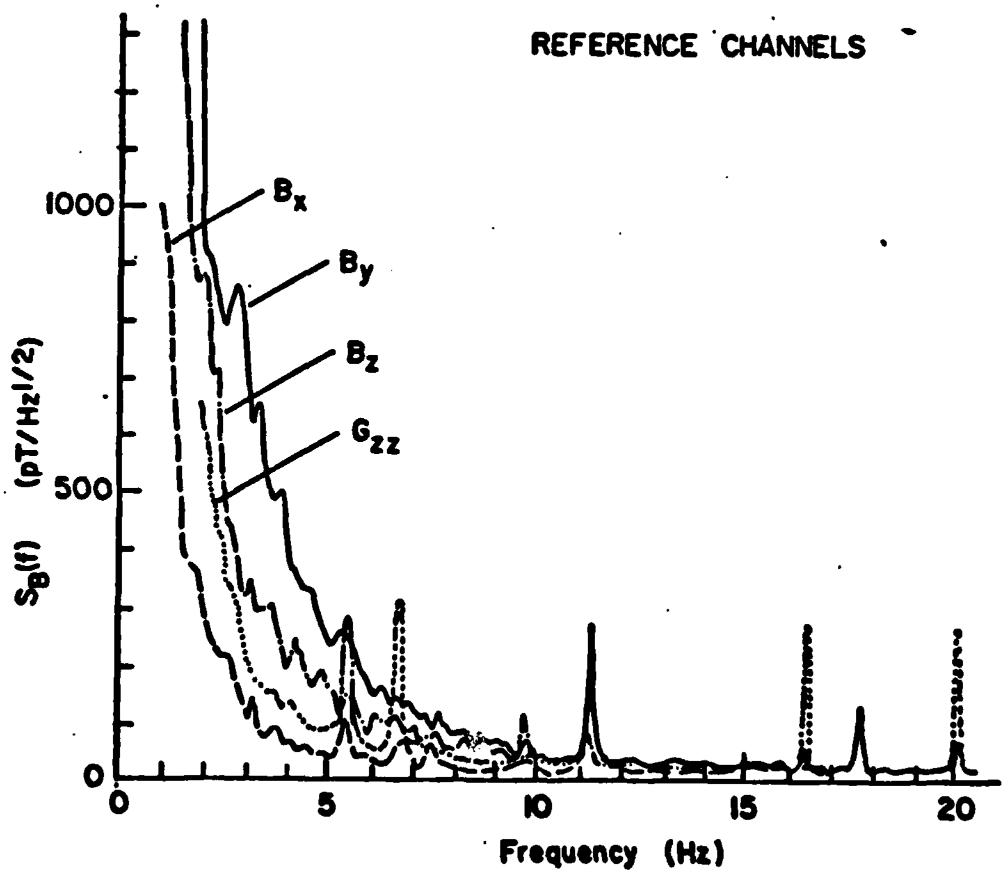

Fig. 5 Reference noise spectra for three field components and the vertical field gradient G_{zz} in the Neuromagnetism Laboratory at New York University. The field gradient is scaled to give the same level of noise on the graph as the field noise at high frequencies.

spectra are displayed in Ref. 8, but at 1 Hz the amplitudes are much higher than in these other locations. Figure 5 shows that the field noise is markedly anisotropic, with strongest components lying in the Y and Z directions. These happen to lie in the plane that is normal to the closest subway line, which is located about 30 m west and 40 m below the laboratory, but as yet this cannot be unambiguously identified as the principal source of noise.

The effect of electronic balancing is illustrated in Fig. 6, which displays the field spectral density for a signal channel. Without electronic balancing, the ambient noise first appears above the intrinsic noise in the frequency range 15-20 Hz. By use of all the references for electronic balancing, the intrinsic noise level of the summed signal could be extended to below about 5-8 Hz before the ambient noise became apparent in a linear plot as illustrated in Fig. 6. Without electronic balance the low frequency noise exhibited a power law of the form f^{-n} where $n \approx 1.9$; and with balance the exponent changed to $n \approx 1.4$. Thus, electronic balance improves the noise level by a factor of 2-3 at about 3 Hz, and this factor increases with decreasing frequency. The noise level of the summed signal channels has been better than that of a conventional single-sensor system with a dc DYNABIAS SQUID that relies on moveable superconducting tabs for trimming the balance.

The ratio of ambient field noise at 3 Hz to the observed noise in a summed signal channel is roughly 2.5×10^3, so this may be taken as the effective rejection ratio. Thus when carrying out the electronic balancing procedure in our environment, the uniformity of the applied field need not be much better than this ratio. This is why the noise spectra did not appreciably change when we made fine

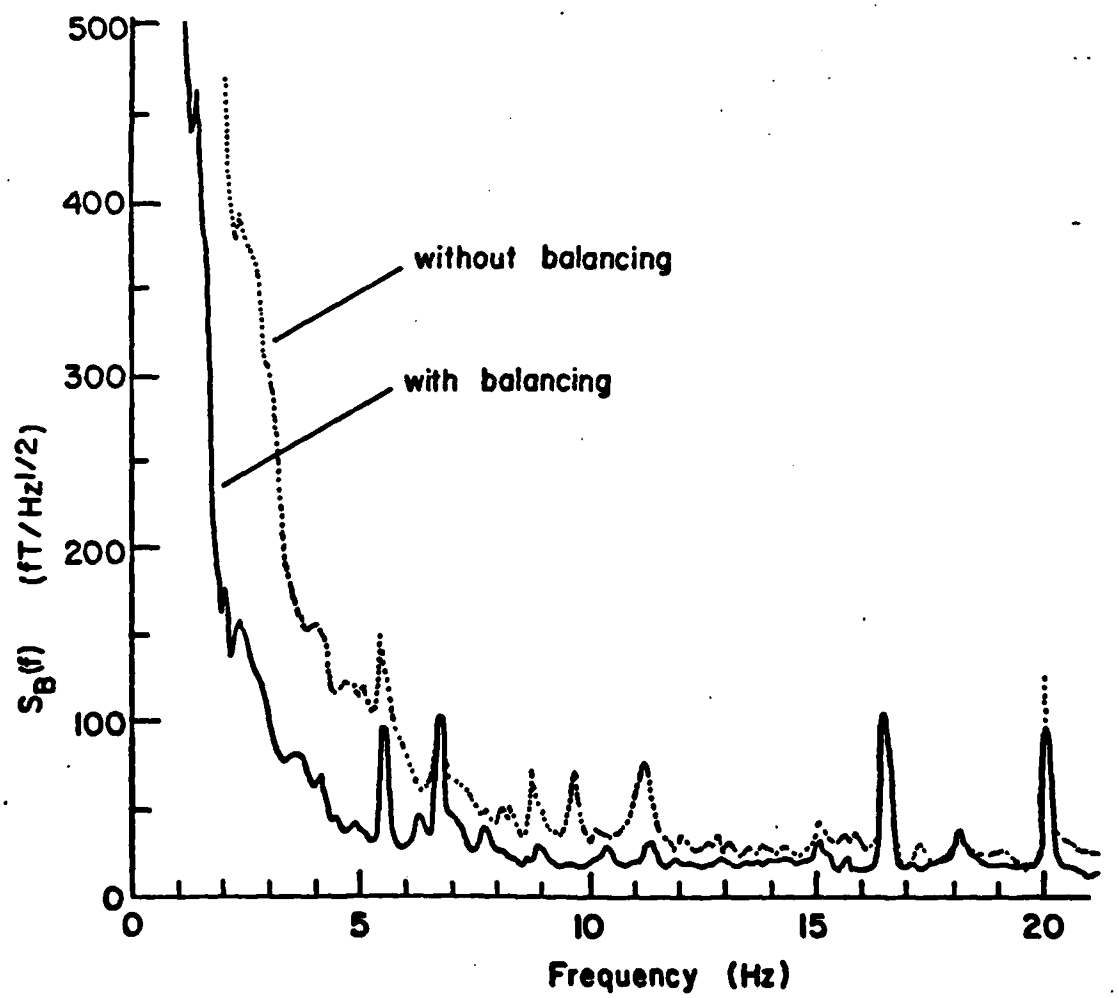

Fig. 6 Noise spectra of a signal channel with and without electronic balancing.

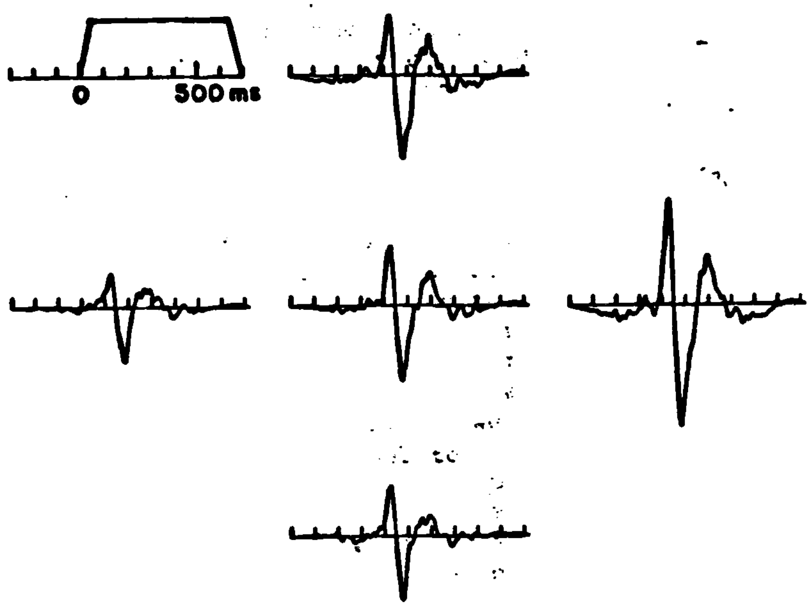

Fig. 7 Five channels of the auditory evoked response

adjustments to the uniformity of the axial field. The remaining noise level at low frequencies in the summed signals is not primarily due to uniform field or gradient noise. Indeed, this inference is supported by studies of the correlation between the summed signal channels and the field and gradient references. The summed signal channels were generally better correlated with each other than with the reference channels.

(b) Evoked responses

One of the advantages provided by a multi-sensor system is the capability of performing simultaneous measurements at a number of locations. The field pattern then may indicate directly the location of the source and whether two or more sources are active. Figure 7 illustrates an example, where the five traces are the measured responses to an auditory stimulus, consisting of the onset of a 2-kHz tone. The shape of the tone's amplitude is shown at the upper left, and the five traces arranged in a cross according to the placement of the signal coils are each the average of 400 responses. The center signal coil was positioned 8 cm directly above the right ear of the subject, and as the traces suggest, there is a maximum amplitude near the most anterior position (on the right of the figure). This region of comparatively strong field arises from neural activity in the auditory cortex,[14,15] and there is another region of opposite polarity on the anterior side of the source, approximately 7 cm from the most anterior position shown here. These traces represent measurements separated by less than 1.7 cm across the scalp, and they clearly show the rapid variation in signal amplitude with position. Similiar sharp variations are exhibited by other neuromagnetc signals, as described in the reviews contained in references 1, 2, and 3. Such observations are sufficient to motivate further development of multi-sensor arrays, so that the entire pattern may be obtained simultaneously.

CONCLUSIONS

This work shows that a multiple SQUID system can be operated successfully in an unshielded urban environment using electronic balancing techniques and achieve better performance than a conventional single sensor system. The application of multiple sensors will greatly enhance the efficiency and effectiveness of neuromagnetic studies for basic and clinical research.

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